UNPUBLISHED PRELIMINARY DATA

THE SPACE, TIME, AND ENERGY DISTRIBUTIONS OF

THE PROTON BEAM OF THE HARVARD UNIVERSITY

SYNCHROCYCLOTRON

R. T. Santoro

OAK RIDGE NATIONAL LABORATORY
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Neutron Physics Division

THE SPACE, TIME, AND ENERGY DISTRIBUTIONS OF THE PROTON BEAM
OF THE HARVARD UNIVERSITY SYNCHROCYCLOTRON*

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ABSTRACT

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The space, time, and energy distributions of the proton beam of the
Harvard University Synchrocyclotron were measured. The spatial distribu-
tion was estimated from multiple-scattering approximations and measured
by means of x-ray films and a beam profile counter telescope. Experimen-
tal results may be approximated by a Gaussian function with $\sigma = \pm 0.28$ cm,
with agreement between the observed results and the multiple-scattering
estimates being favorable. Ninety-eight percent of the protons were con-
tained in an 0.84-cm beam radius. Analysis of the macroburst structure
revealed a gross duty cycle of $(4 \pm 2)\%$, depending upon proton injection
and extraction parameters. Oscilloscope observations of the microstruc-
ture showed that the protons occurred at regular 42-nsec intervals, with
the width of the time distribution of protons being less than 7 nsec.
With the delayed coincidence technique, the standard deviation of the
time between adjacent bursts of protons was 1.4 nsec.

The proton beam energy was determined from measurements of the pro-
ton range in copper and from time-of-flight measurements. The beam
energy determined from the range measurements was 160.3 ± 0.6 MeV. The
rms range spread was measured from the differential range curve as $0.34 \pm
0.05$ g/cm^2, compared with the calculated straggling standard deviation
of 0.32 g/cm^2. The proton energy measured by flight-time analysis over
a 355-cm flight path was 153.38 ± 4.1 MeV.

INTRODUCTION

Experiments performed at the Harvard University Synchrocyclotron[1,2] to determine the energy spectra at various angles for secondary neutrons, protons, and gamma rays required that the space, time, and energy distributions of the proton beam be well known. Knowledge of these parameters was necessary for the design of experimental instrumentation and for the analysis of the spectral data.

The synchrocyclotron (shown in Fig. 1) is shielded by concrete 3 to 8 ft thick and is a frequency-modulated machine capable of producing unpolarized 160($\pm$2%)-MeV protons at rates as high as 5×10^{10} protons/sec. Modulation is achieved with a rotating 16-tooth condenser through a frequency range of 23 to 30 Mc/sec.

Following extraction, the beam is passed through three sets of collimating slits, a steering magnet, and finally a quadrupole magnet. Beam location is controlled by the steering magnet, and focusing is achieved by optimizing the slit openings and the quadrupole magnet current.

BEAM DISTRIBUTION IN SPACE

The spatial distribution of protons perpendicular to the beam axis was measured to determine the region where primary reactions might have occurred in the bombarded target. The distribution at the target was estimated from multiple-scattering distribution approximations and was experimentally determined from measurements made with x-ray films and a beam profile counter telescope. The results were compared and the fraction of protons striking the target was estimated. For all spectral measurements,[1,2] the size and shape of the beam were essentially the same, and the results of calculations for estimating proton losses are applicable in all experiments.

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1. Neutron Phys. Div. Ann. Progr. Rept. Aug. 1, 1963, ORNL-3499, Vol. II.

2. Neutron Phys. Div. Space Radiation Shielding Research Ann. Progr. Rept. Aug. 31, 1962, ORNL CF-62-10-29 (Rev.), pp. 182-263.

ION SOURCE

HARVARD UNIVERSITY
95−in. SYNCHROCYCLOTRON

STEERING MAGNET

"A" SLIT

"B" SLIT

SHIELD WALL
(3 TO 8 ft OF CONCRETE)

QUADRUPOLE MAGNETS

HV

"C" SLIT

EXIT PIPE

BEAM MONITOR ION CHAMBERS

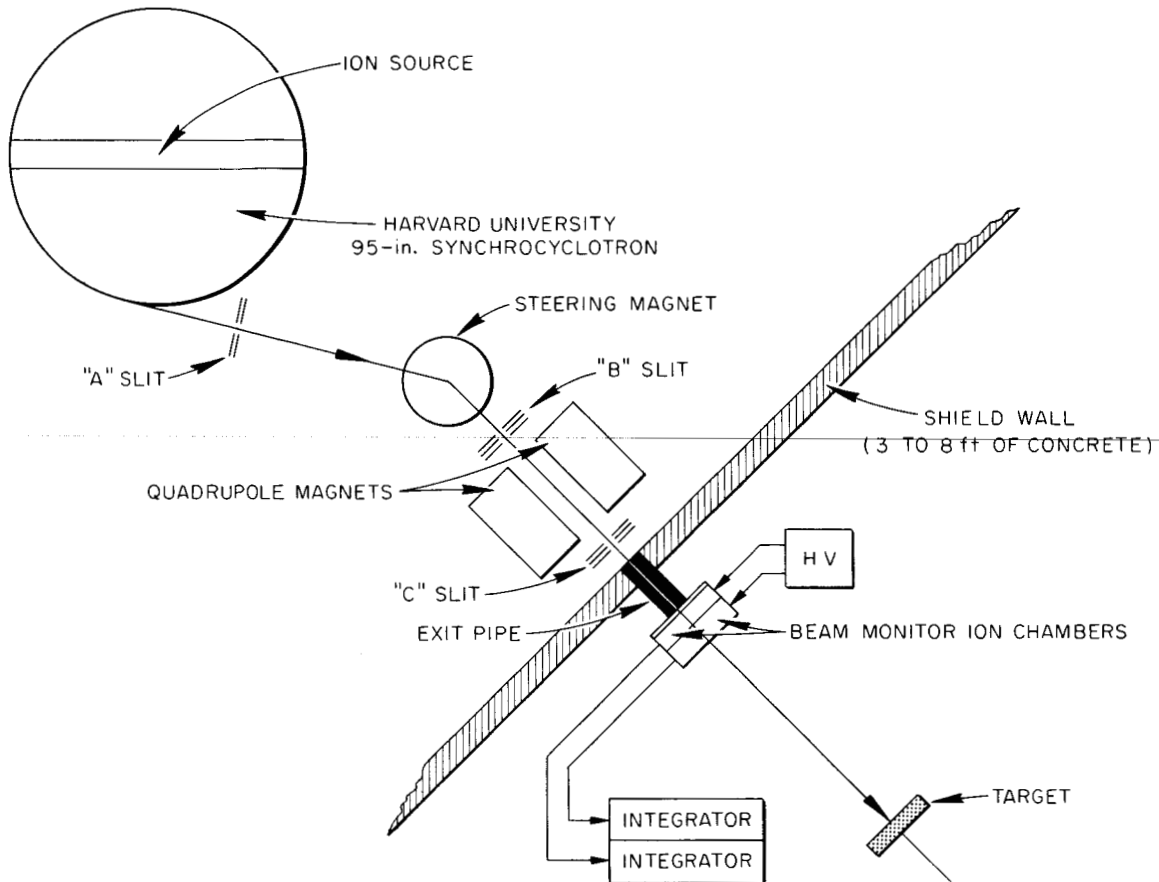INTEGRATOR

INTEGRATOR

TARGET

Fig. 1. Component Diagram of the Harvard University Synchrocyclotron.

Calculation of the Proton Distribution

When charged particles pass through materials of finite thickness, they undergo large numbers of electromagnetic collisions. The sequence of multiple collisions is characterized by numerous randomly oriented small-angle deflections, together with a smaller fraction of large-angle single-scattering deflections.

The scattering of these particles may be represented by the root-mean-square angle of scattering θ_{rms}, and when the multiple scattering dominates, the rms angle is proportional to the square root of the thickness of the scatterer. The scattering gives rise to a spread of the beam perpendicular to the direction of motion. The distribution of protons after multiple scattering can be approximated by a Gaussian function given by

$$P(r) = (\pi r_0^2)^{-1} e^{-(r/r_0)^2} , \qquad (1)$$

where $P(r)$ is the probability per unit area of finding a particle with rms displacement, r, from the beam axis:

$$r_0 = \theta_{rms} D , \qquad (2)$$

with D being the distance from the scatterer to the point at which the distribution is measured. Equation (1) gives the first-order approximation to the multiple-scattering distribution.

Snyder and Scott,[3] using Fourier transforms, obtained a general expression for the scattering density function including all orders of scattering. They give the results of their calculations in graphic form over a wide range of target thickness and scattering angle. Figure 2 compares the full Snyder-Scott results with the (Gaussian) multiple-scattering approximation. The notation used is that of Snyder and Scott: η is proportional to the projected scattering angle θ_y, and $q(s,\eta)$ is proportional to the probability density

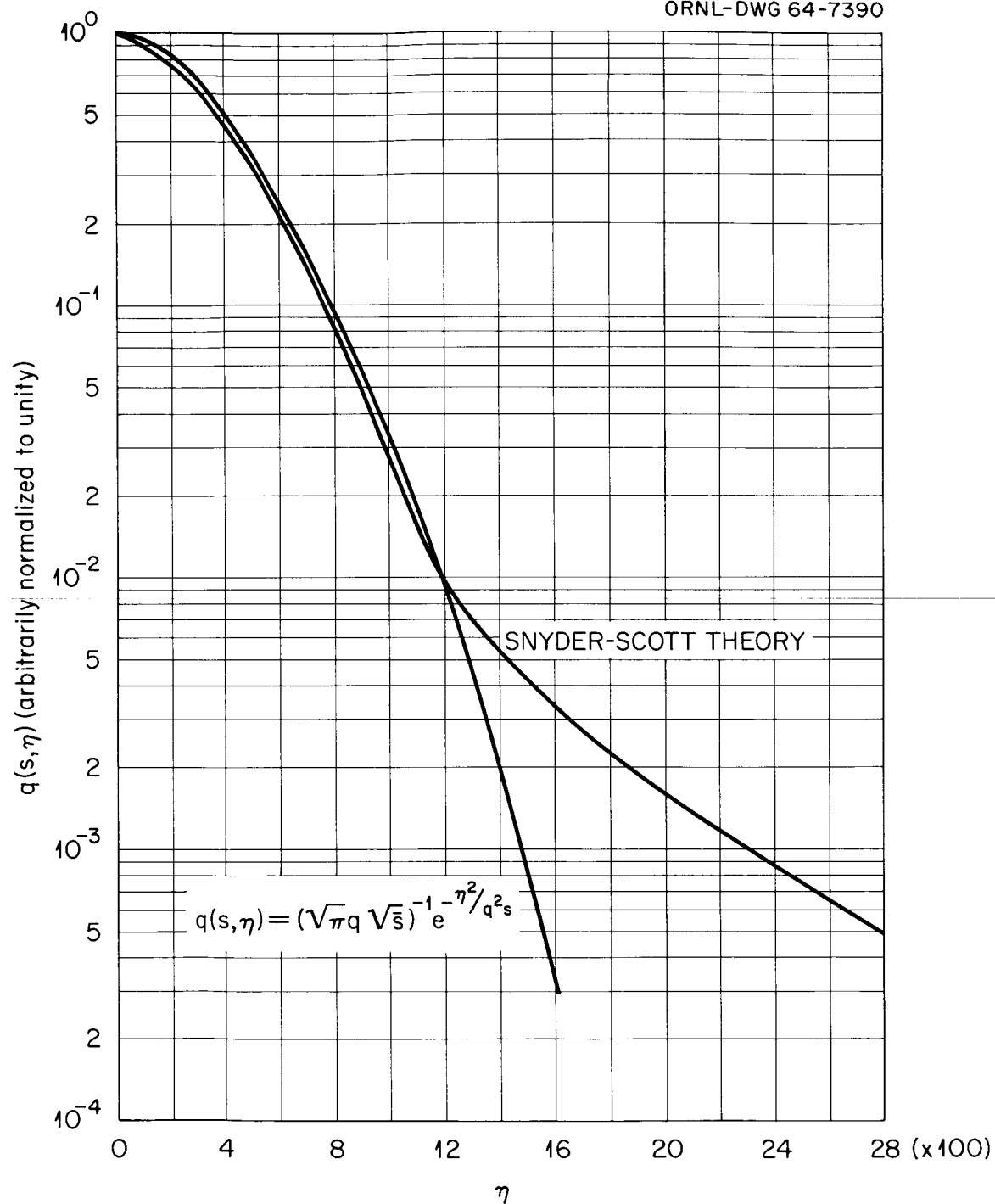3. H. S. Snyder and W. T. Scott, Phys. Rev. 76, 270 (1949).

Fig. 2. Comparison of the Snyder-Scott Scattering Distribution with the Gaussian Approximation for $q(s,\eta)$ vs η with $q^2 = 15.4$, $\bar{s} = 21,000$.

function defining the fraction of protons in an angular interval $d\theta_y$ about θ_y. The scatterer parameters were chosen similar to those encountered in this experiment.

Plotting the results of Fig. 2 on a linear graph reveals that the ratio of the area between the Gaussian curve and the scattering tail to the area in the peak is negligible. The Gaussian multiple-scattering approximation gives sufficiently accurate results for estimating the scattering distribution at the target plane.

For this report, the scattering distribution at the target plane is obtained by using the Gaussian approximation only, and the fraction of protons at the target is calculated by the procedure suggested by Sternheimer.[4]

The rms angle of scatter of Eq. (2) is calculated from the expression

$$\theta_{rms}^2 = \left(\frac{E_s}{\beta c p}\right)^2 \sum_i \frac{x_i}{(X_s)_i} , \qquad (3)$$

where E_s is a constant equal to 21 MeV, βc is the velocity of the incident particle, p is its momentum, $(X_s)_i$ is the multiple-scattering length in g/cm^2 of the ith scatterer material, and x_i is the thickness of the material in the beam. The scattering distribution is determined for the passage of the proton beam through the two monitor ionization chambers shown in Fig. 1. The combined scattering length of the chambers is obtained from the summation in Eq. (3). In passage through the chambers, the beam is scattered by 8 mils of aluminum, 2.5 mils of aluminized Mylar, and 5.0 cm of helium gas. Included is an additional 5-mil-thick Mylar beam pipe window. The scattering length of the combination of materials is equivalent to 0.078 g/cm^2 of aluminum, where $(X_s)_{Al} =$ 23.9 g/cm^2. This value is used in all subsequent calculations. Defining

$$\rho' = \rho_o/R$$

4. R. M. Sternheimer, Rev. Sci. Instr. 25 (11), 1070-1075 (1954).

and

$$r' = r_o/R \quad ,$$

where ρ_o is the rms radius of the assumed normally distributed unscattered beam, r_o the rms scattering radius as in Eq. (2), and R the radius of the target; the fraction, f_p, of protons striking the target may be obtained directly from Sternheimer's curves. The value for ρ_o, for this reporting, must be estimated since in the experiment no measurements were made of the unscattered beam radius. However, from photographs made at various points along the beam axis, reasonable estimates for the unscattered beam radius give $\rho_o = 0.17$ cm. The results of these calculations are given in Table 1.

Experimental Results

The beam distribution was experimentally determined by exposing five x-ray film plates in a beam of nominally 4×10^6 protons/sec. The exposure, determined from the charge collected in the ionization chambers, was made over a range of 1.6 (± 0.080) x 10^7 to 1.3 (± 0.065) x 10^9 protons. The individual plates were developed simultaneously to ensure uniform transparency in the unexposed portions of the film. Initial analysis was achieved by measuring the fraction of light transmitted through the image by scanning with a photodensitometer. The slit openings of the densitometer were adjusted for a minimum opening of 10-μ width and 0.7-mm height. The scanning speed was 5 mm/min. The results of scanning the five plates are shown in Fig. 3. The profiles were aligned by defining the center of the full width at half maximum (FWHM) value of the transmission curves as the beam center line. From these data it was possible to construct the composite distribution curve shown in Fig. 4. This was done as follows.

1. The peak of the 1-nanocoulomb exposure curve, shown in Fig. 3 and defined as unit relative beam intensity, was plotted as point A on Fig. 4.

2. Following a line of constant transmission, shown by the dotted line in Fig. 3, the remaining transmission curves were intercepted at

TABLE 1. Comparison Between the Estimated Fraction of Protons, f_p, and Experimentally Measured Fraction of Protons, f_d, Striking the Target as a Function of the Target Radius R

R (cm)	$r' = \dfrac{r_o}{R}$ (a)	$\rho' = \dfrac{\rho_o}{R}$ (b)	f_p	f_d
3.8	0.083	0.044	1	1
0.84	0.376	0.202	0.98	0.98
0.56	0.564	0.304	0.94	0.86
0.28	1.120	0.607	0.35	0.39

[a] Based on $r_o = 0.316$ cm, $D = 101.6$ cm, and $\theta_{rms} = 3.11 \times 10^{-3}$ radian.

[b] $\rho_o = 0.17$ cm.

EXPOSURE

o 1 ncoulomb   □ 50 ncoulomb

△ 5 ncoulomb   ▽ 100 ncoulomb

◊ 10 ncoulomb
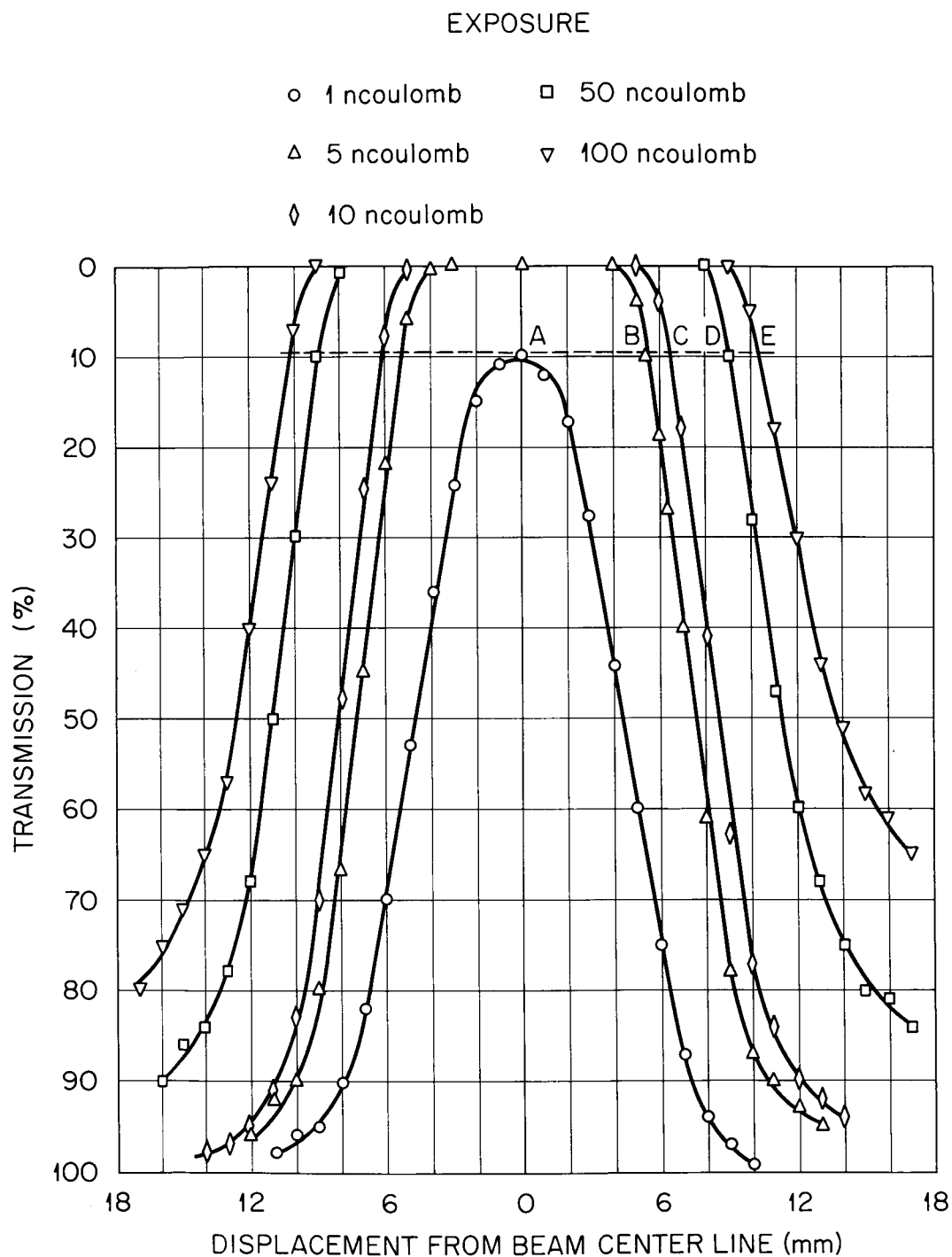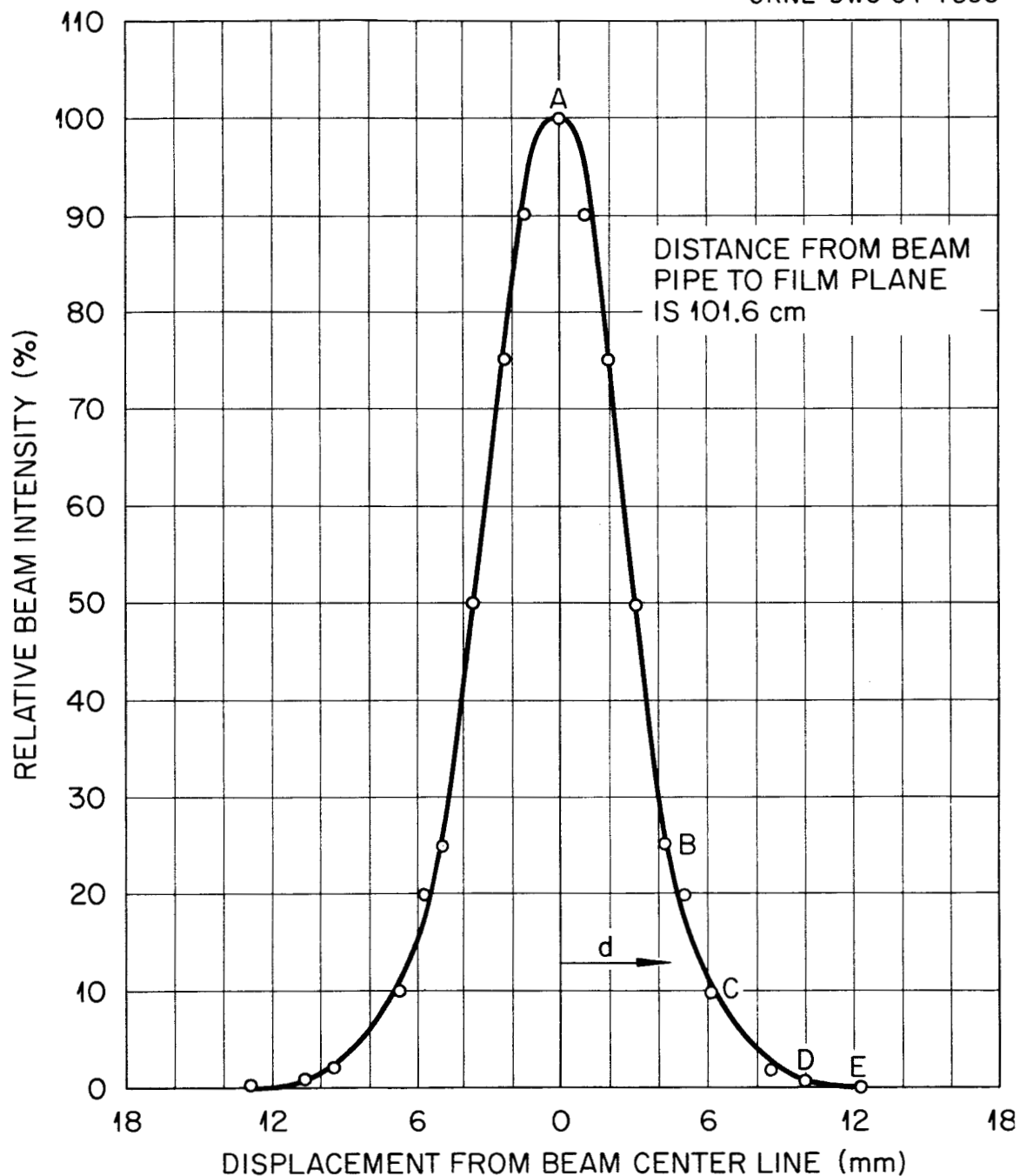

Fig. 3. Percent Transmission vs Image Width for Kodak Type-M
Industrial X-Ray Film.

Fig. 4. Composite Proton Distribution Curve. This curve is derived from Fig. 3 and plots the relative beam intensity as a function of beam diameter for Kodak Type-M industrial x-ray film.

points $\underline{B}$, $\underline{C}$, $\underline{D}$, and $\underline{E}$. Point $\underline{B}$ has the same width dimension as the 20% transmission level on the first curve, for example. The remaining points beyond these four were estimated from a calibration curve of the exposure-film density relationship obtained from the transmission curve data of Fig. 3.

The proton distribution was also measured with the profile telescope shown in Fig. 5. The distribution was obtained by scanning horizontally and vertically perpendicular to the beam axis and recording coincidence counts for fixed increments of integrated beam current as a function of displacement from the beam center at a distance of approximately 1 m from the ion chamber. The values obtained for FWHM for both the vertical and horizontal scan as well as other points on the distributions were in agreement, suggesting that the beam cross section was essentially circular. Figure 6 plots proton intensity as a function of the distance from the beam center line as obtained with the profile telescope.

The distribution curves in Figs. 4 and 6 are essentially Gaussian in shape. It was assumed from the exposures that the beam cross section was very nearly circular. If both conditions are true, the fraction of protons f_d contained within a radius d may be estimated from integration of a Gaussian frequency curve for the fitted value of $<d^2>^{1/2} =$ 0.28 $\pm$ 0.01 cm. Agreement between the x-ray film exposures and profile telescope data is excellent. Using the Gaussian frequency curve given above, integration of the curves in Figs. 4 and 6 gives the same results for f_d as shown in Table 1.

<center>Beam Location Stability</center>

Measurements of the time drift of the beam location with respect to the target center line were made with Polaroid film exposures in the target plane. Initially, the beam was centered on the target by proper location of the spectrometer holder and target positioning device. The location of the beam was checked several times during a particular experiment. It was observed that the beam drift was less than 5 mm/day with respect to the target center. Corrections for the drift were made by adjustment of the steering magnet.

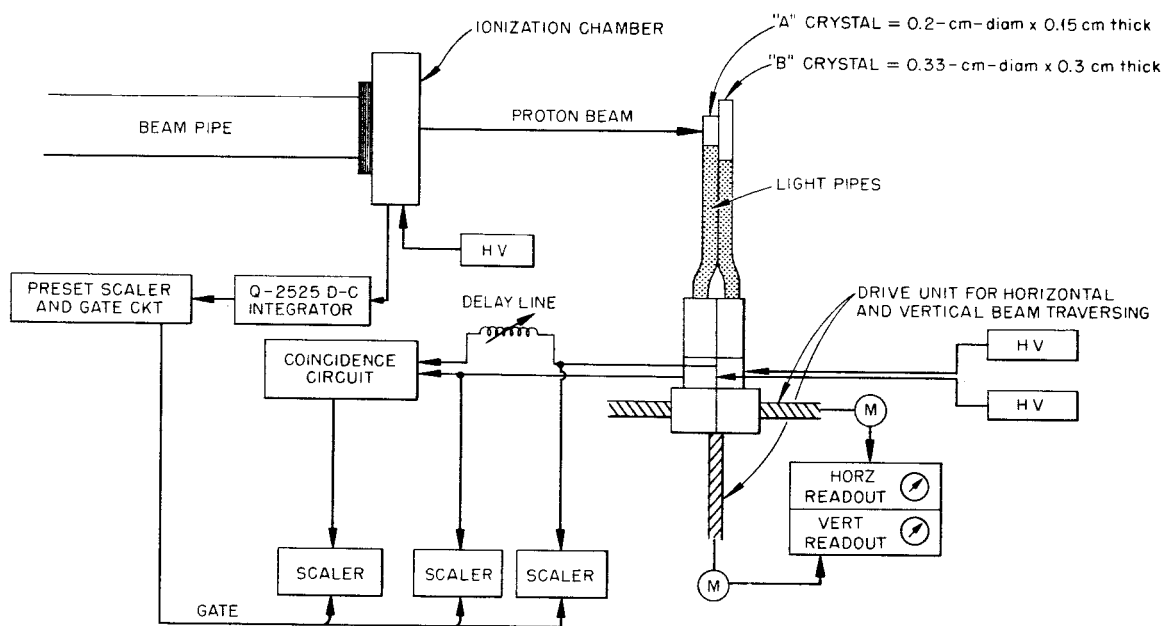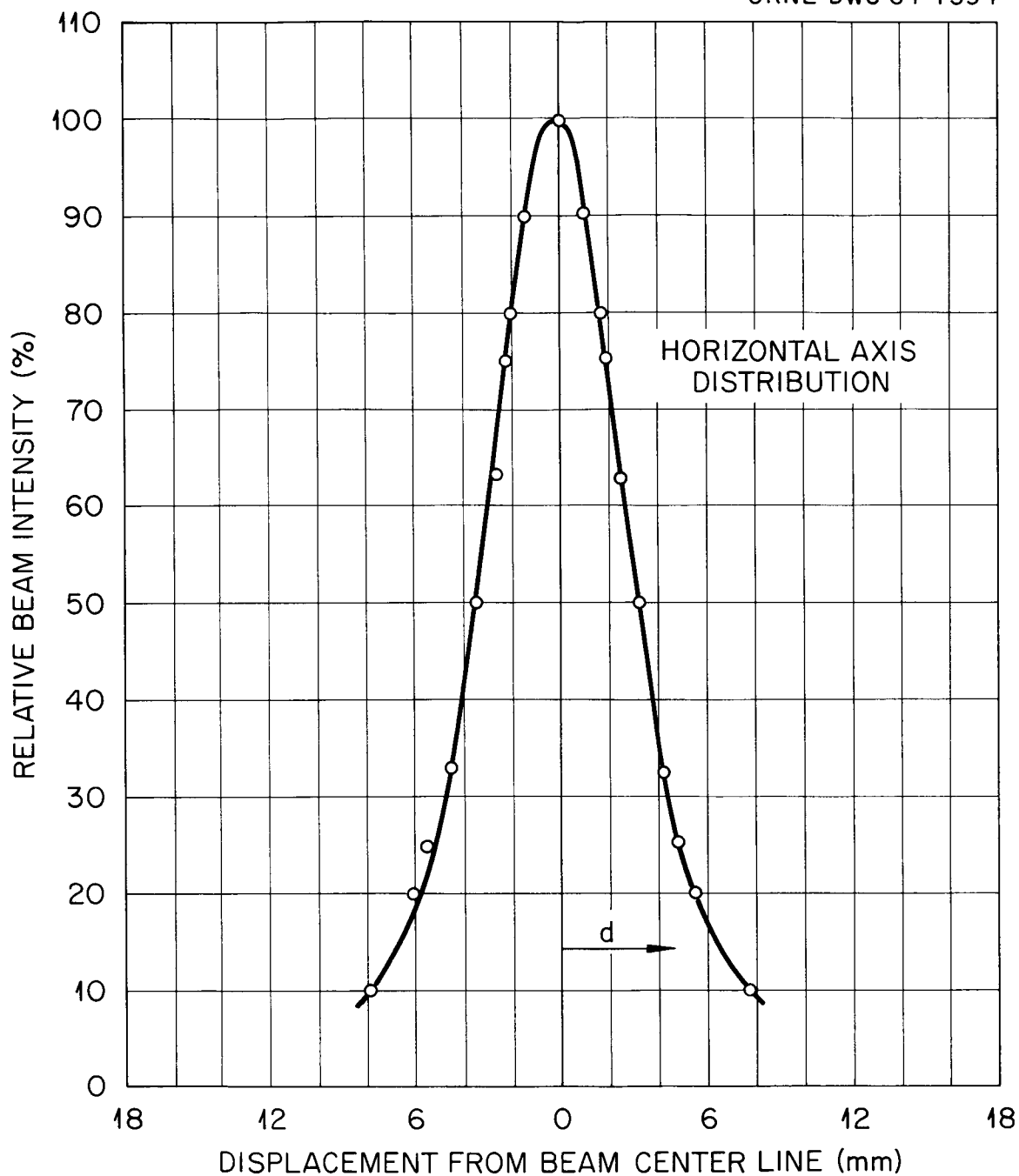Fig. 5. Block Diagram of the Profile Telescope and Instrumentation.

Fig. 6. Proton Distribution Curve Obtained with the Profile Tele-
scope. Relative beam intensity vs beam diameter. Distance from beam exit
pipe equals 101.6.

DISTRIBUTION IN TIME

The distribution of the proton beam in time was determined from the measurement of the gross structure of the beam associated with the modulation frequency (macrostructure) and the fine time structure due to the r-f accelerating frequency (microstructure). In a synchrocyclotron the proton beam is extracted only when the frequency of the accelerating voltage is within a narrow range. In the Harvard synchrocyclotron, frequency modulation is achieved by a 16-tooth rotating capacitor operated at nominally 18 rps. Consequently, there are 288 bursts of protons per second. Because of variations in the shape of the capacitor teeth, wobble in its shaft, and variations in the rotation speed, the shape of the individual proton bursts varies in intensity and duration. In order to assess the effect of variation of the machine parameters on the gross duty cycle, the macroburst structure was studied as a function of ion source position and extraction frequency.

Measurement of the Macrostructure

The burst structure was measured with the circuit shown in Fig. 7. An organic detector was positioned in the beam. A marker pulse was available on the downswing of the FM cycle just before proton extraction; so the elapsed time between the marker pulse and a subsequent proton signal was analyzed and stored. The macrostructure was analyzed for the bursts associated with selected teeth of the rotating condenser and also for the composite structure. The duty factor was measured for the composite structure.

The gross duty factor can be obtained by measuring the ratio of the square of the average height of the burst to the average value of the height squared. The burst height is proportional to the output current from the detector used in Fig. 7. So the duty factor is obtained from

$$df = \frac{< \bar{I} >^2}{< I^2 >} \quad , \tag{4}$$

where I is the time-dependent phototube current averaged over the rf (22 Mc) fine structure.
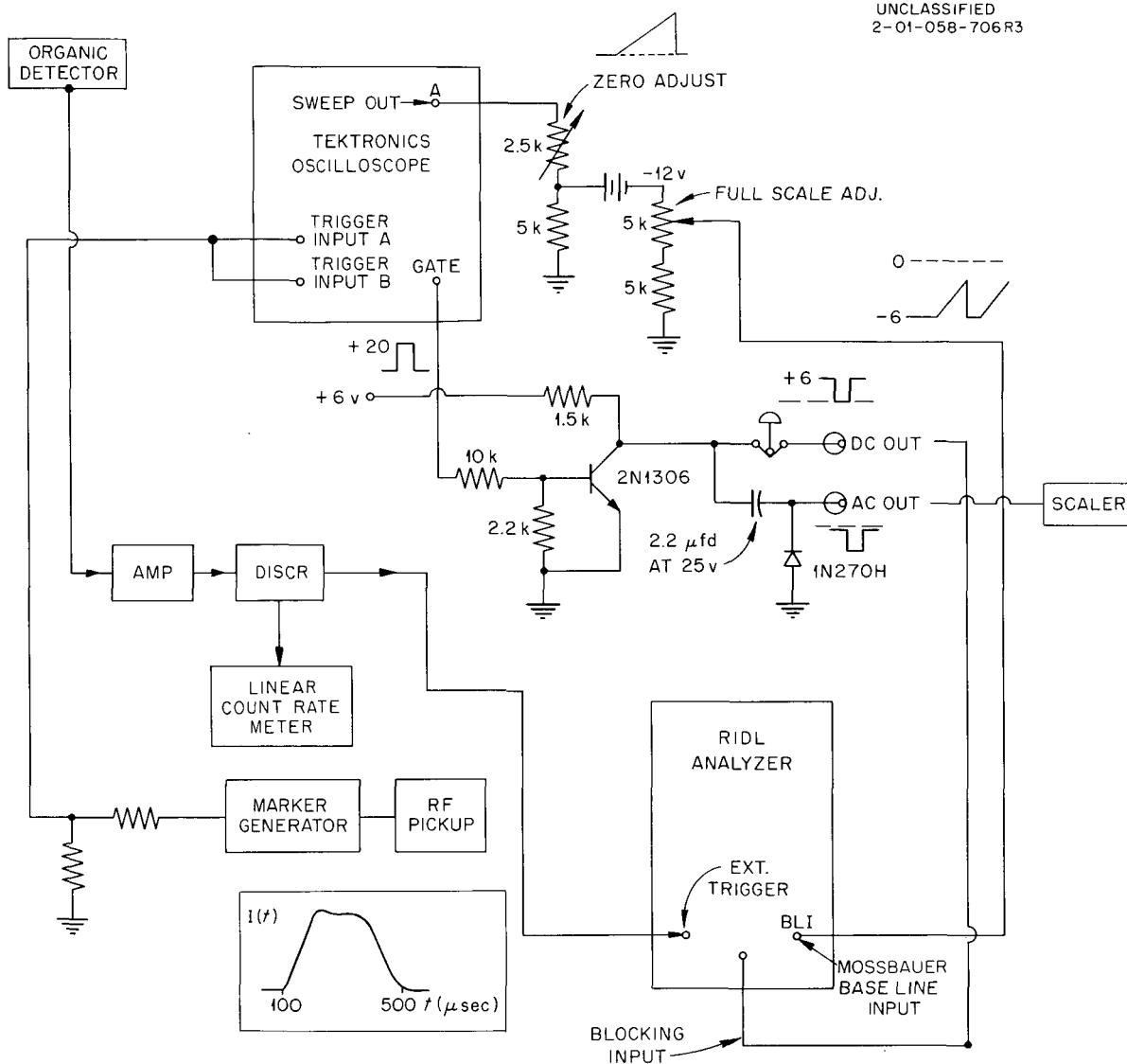
Fig. 7. Circuit Used for Measuring the Beam Macrostructure. This circuit utilizes the Mossbauer base-line input provisions of the RIDL pulse-height analyzer. With this mode of operation, the analyzer associates a channel with the voltage of the negative pulse feeding this input at the time that the trigger pulse arrives from the proton detector. Zero volts corresponded to channel zero, and -6V was channel 100. With the oscilloscope sweep set at 50 μsec/cm and synchronized with the extraction-time marker pulse, an analyzer-enabling gate signal is generated each time the frequency passes through the extraction point. Thus a trigger pulse causes storage in a channel corresponding to the time that a proton appeared in a macroburst relative to the phase of the frequency modulation.

A typical composite burst shape is shown in the inset in Fig. 7. By approximating the burst by a triangle, rectangle, or both, the macroduty factor can be obtained quite readily by using this definition. Typical values obtained were $(4 \pm 2)\%$. The value obtained by Lefrancois[5] using Eq. (4) to evaluate current from a phototube viewing a plastic scintillator was $(3 \pm 0.2)\%$. Zobel and Maienschein[6] have reported values ranging from 2.4 to 4.9% by measuring random coincidence events during several runs. Values for the duty cycle of 2.2 to 4.55% were measured for a 5% variation in the extraction frequency, and 2.8 to 4.9% for variations in the ion source orientation at the extraction frequency of maximum duty factor.

In calculations that Peelle and Cowperthwaite[7] made by using data from individual proton-counting measurements, the duty factor was measured as 2% for very low counting rates and narrow "B" slit openings (see Fig. 1).

Measurement of the Microstructure

A further study of the burst structure reveals a finer distribution of protons, called the "microstructure," with bursts occurring at the rf accelerating frequency. Knowledge of the microstructure was essential in the design of fast-timing circuits and gating circuits. The gating circuits were used to enable the detectors to operate only during the microbursts to minimize the accumulation of background counts due to secondary neutrons.

In measuring the microstructure an oscilloscope was used to observe individual proton pulses from a detector placed in the beam, together with the beam profile telescope, for which delayed coincidence techniques were used.

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5. J. Lefrancois, Rev. Sci. Instr. 32, 986 (1951).

6. W. Zobel and F. C. Maienschein, private communication.

7. Neutron Phys. Div. Ann. Progr. Rept. Aug. 1, 1963, ORNL-3499, Vol. II, p. 73.

The pulses from an organic scintillator placed in the proton beam were used simultaneously to trigger an oscilloscope and provide the vertical input. The fine time structure was measured by observing on the cathode ray tube the relationship between the proton-induced trigger pulse and the pulse formation due to subsequent protons. The pulse frequency was constant, nominally 22.7 Mc/sec, with the width of the distribution of protons being less than 7 nsec. Observations made of the microstructure for many thousand pulses showed that the pulses occurred at regular intervals of ~ 42 nsec, and in no case was there any evidence of structure between the main pulses.

In the microstructure measurements with the profile telescope, the delay in one leg of the circuit was varied until coincidence was established between successive bursts. The amount of delay is the time between bursts. The telescope, initially set up to measure the beam profile, was located at one edge of the beam in order to count approximately 1 proton/sec. Typical resolution for coincidence varied from 3.5 to 6.2 nsec, depending on the coincidence circuit used. The required delay to establish coincidence between microbursts varied from 41.2 to 44 nsec, with the breadth of the peak varying from 4.5 to 6.3 nsec for the above resolving times. Typical results are shown in Fig. 8.

The time spectra of Fig. 8 can be approximated accurately by a Gaussian distribution, and its variance computed by the usual methods. The coincidence resolution curve is approximately trapezoidal in shape. The time distribution of pulses in adjacent microbursts can be calculated by taking the difference between the variance of the Gaussian and that of the trapezoidal distributions. The value obtained for the standard deviation of the time between pulses in adjacent bursts is 1.4 nsec.

PROTON ENERGY DISTRIBUTION

The energy distribution of the proton beam was determined from measurements of the proton range in copper and from flight-time measurements. These measurements were made in order to determine the energy of the beam after passage through the monitor ionization chambers shown in Fig. 1.
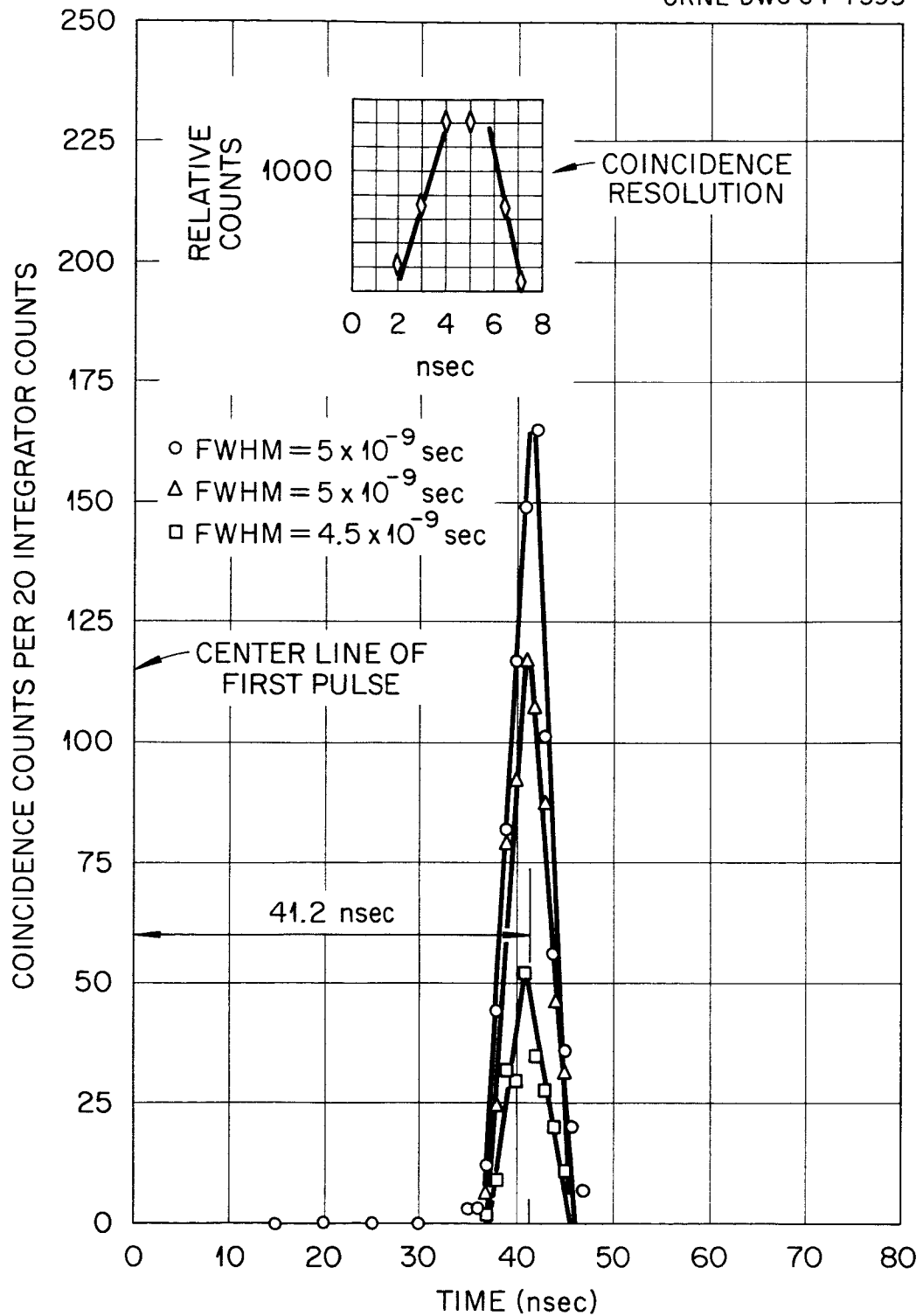
Fig. 8. Measurement of Microstructure.

Beam Energy from Proton Range in Copper

Two independent measurements were made of the proton range in cop-
per, one by Johnson[8] (in September 1962) and the other by Santoro and
Love (in January 1963), and different absorber blocks and detectors were
used.

Two detectors were located in the beam path as shown in Fig. 9.
The coincidence counts were recorded as a function of the thickness of
the absorber placed between the two detectors for a fixed number of pro-
tons measured by the "A" detector, and are plotted in Fig. 10 for both
measurements. The energy is determined from the curve by treating the
maximum slope of the integral curve (the peak of the differential curve)
as the mean range from protons of the incident energy in copper. This
corresponds approximately to one-half the count rate with no absorber
present.

The Range from Johnson's Measurements.-- The amount of copper pres-
ent at the mean range was 26.326 g/cm^2. Preceding the copper were
51.4 cm of air, 0.159 cm of CH, and 0.0051 cm of Al, corresponding to
$0.062, 0.168$, and 0.014 g/cm^2 surface density, respectively, for each
material.

The ratio of $(dE/dx)_R$, the average energy loss per unit path length
of a given material R, to $(dE/dx)_{Cu}$ is a slowly varying function of en-
ergy, and conversion to equivalent copper thickness depends only on
approximate values for the incident energy. Using 160 MeV to evaluate
these ratios, Johnson obtained a total copper-equivalent thickness of
0.348 g/cm^2. Including an additional 0.011 g/cm^2 copper equivalent
thickness for the small amount of air between the absorber and the "B"
detector, the total amount of material in the beam was equivalent to
26.755 g/cm^2 of copper.

In these calculations, there were two main sources of error: the
determination of the total copper thickness and the conversion between

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8. C. F. Johnson, private communication. No information was available
   concerning B bias, which is here presumed to be very low. No
   uncertainty was given for determining the mean range from the exper-
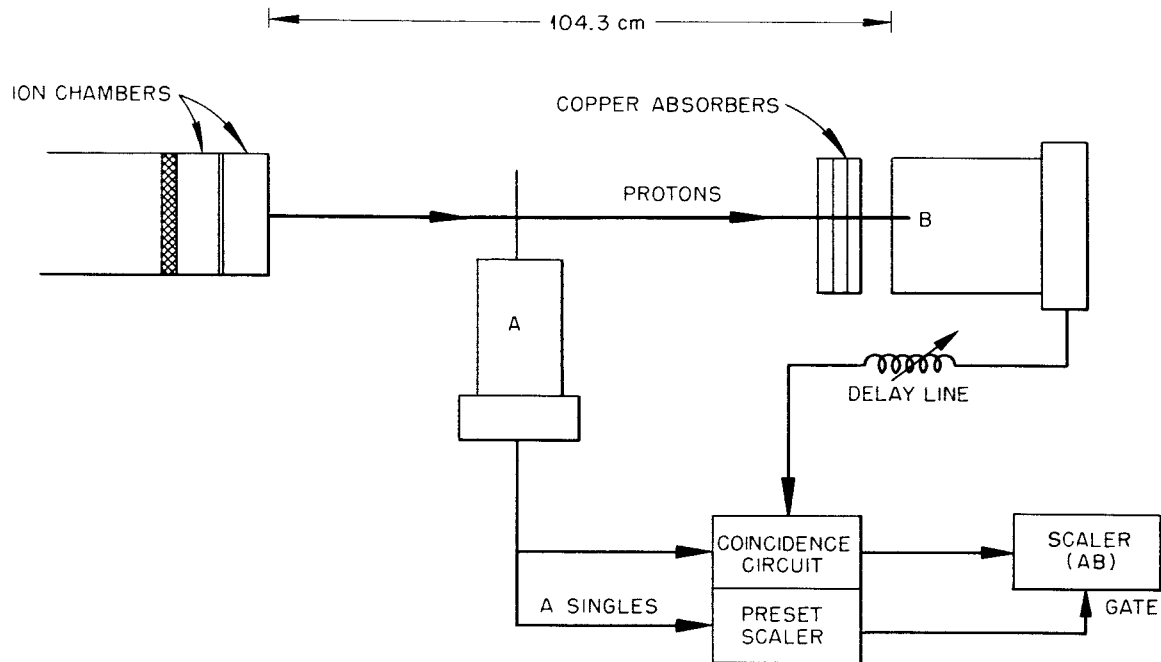   imental data.

Fig. 9. Block Diagram of Circuit Used to Obtain Range-Energy Curve.
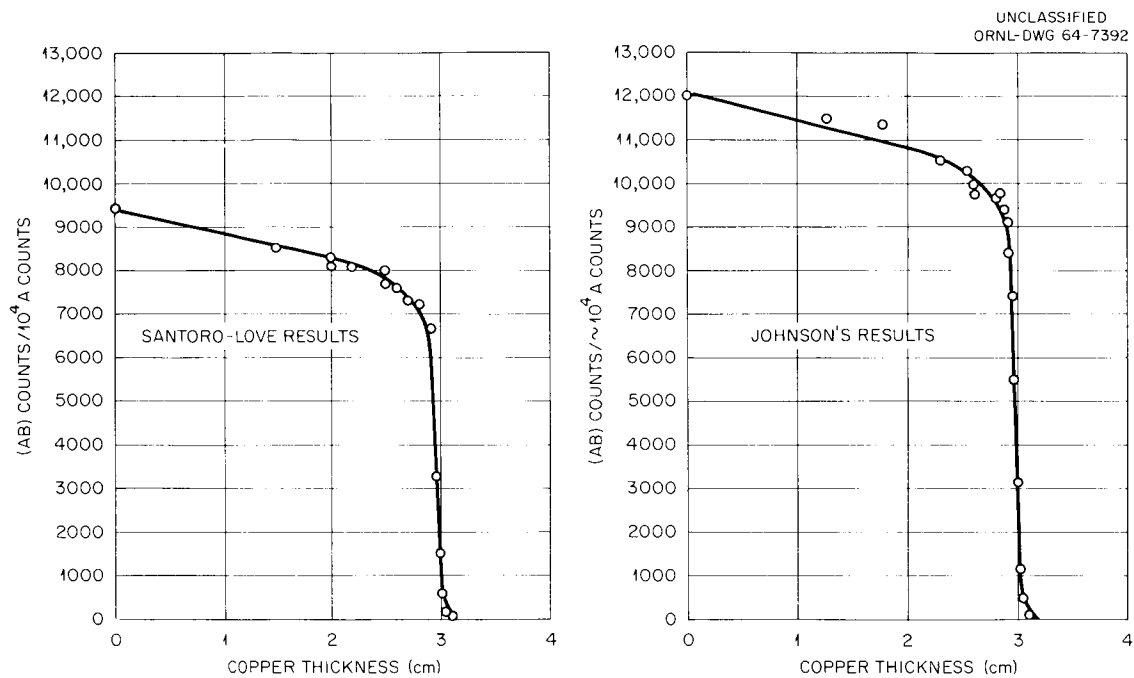
Fig. 10. Pathlength Energy Curves.

the mean range and energy. Measurements of the volume density of the copper introduced a $\pm 0.19\%$ error for one standard deviation based on measurements of the absorber dimensions and weight. Errors due to conversion to energy are discussed later. Then, finally, the mean range obtained by Johnson for the beam protons in copper is 26.755 $\pm$ 0.051 g/cm^2.

Range Due to Santoro and Love. -- The second of the range-energy measurements was made with the apparatus shown in Fig. 9. The bias level of the "B" detector was set to count protons with energy in excess of 2 $\pm$ 0.5 MeV. The bias was determined by using the 0.511-and 0.393-MeV gamma rays of ^{22}Na and ^{113}Sn, respectively. The uncertainty in the measurement of the energy resulting from the use of this bias setting was less than 0.1%, well within the other uncertainties.

The mean range of the protons was reached with 26.61 $\pm$ 0.1 g/cm^2 of copper. Using a code due to Wachter,[9] the additional material in the beam - the air, detector material, and aluminum detector covers - was calculated in terms of the equivalent thickness of copper as 0.376 g/cm^2, giving a total of 26.98 $\pm$ 0.1 g/cm^2 of copper.

The absorber plates were constructed to tolerances known to be better than 0.1%, and the weight was determined to the same order of magnitude. The volume density values for the air, aluminum, and detector materials were based on published values and since they constitute less than 2% of the material in the beam, only small errors were introduced in the conversion to equivalent copper thickness.

The value for the beam mean range in copper was then determined as 26.98 $\pm$ 0.1 g/cm^2, which is consistent with the value obtained earlier by Johnson and is used in this report to determine the beam energy. This range must be corrected for the multiple scattering of the protons in copper. The correction value, 0.5% in range, was estimated from

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9. J. W. Wachter, ESCALATOR, a program for the IBM-7090 which uses interpolation of range-tables to determine accumulative energy losses through various regions of materials (unpublished).

Bichsel's data for multiple scattering in nickel.[10] The resulting
experimental path length in copper is 27.11 ± 0.1 g/cm^2.

Conversion of Path Length to Energy. -- The conversion of range to
energy is based on published values for the path length of protons in
copper, based on the average energy loss per g/cm^2, dE/dx, obtained from
the integration of the Bethe-Bloch equation

$$\frac{dE}{dx} = \frac{4\pi m_o c^2 r_o^2 N_o}{\beta^2} \frac{z^2 Z}{A} \left(\ln \frac{2m_o c^2 \beta^2}{1 - \beta^2} - \beta^2 - \ln I - \frac{\Sigma C_i}{Z} \right), \quad (5)$$

where

    x = path length, cm,

    z = charge number of the incident particle,

    Z = charge number of the stopping material,

    A = atomic weight,

    $\beta = v/c$, where v is the velocity of the particle and c is the speed
       of light,

    N = Avogadro's number,

    e = electronic charge,

    m_o = rest mass of the electron,

    I = average excitation potential per electron of stopping atom,

    C_i = "shell-correction" term to compensate the effect of nonpartici-
       pating bound electrons.

According to the extent to which corrections are made for the C_i
term and depending on the choice of experimentally determined values for
I, values published for dE/dx may differ by a few percent.

For this report, Bichsel's[10] values are used. These data are
based on recently determined values for I and extensive corrections
using the C_i terms. Additional credence has been given to Bichsel's

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10. H. A. Bichsel, Passage of Charged Particles through Matter,
American Institute of Physics, Handbook, 2nd Ed., McGraw Hill,
1963.

data in a more recent report by Fano.[11] Table 2 shows a comparison, over an energy range of 140 to 180 MeV, between Bichsel's values and those of Peelle,[12] Sternheimer,[13] Rich and Madey,[14] and Williamson and Boujot.[15]

Bichsel[16] has noted a discrepancy between the calculated values for the mean range of protons in copper and those obtained experimentally. In the energy range between 70 to 110, at 150 and 190 MeV, experimental path lengths are 1.5% greater than Bichsel's best computed values. Accordingly, the values in Table 2 for the path length are corrected for the 1.5% difference, and the mean proton energy is computed. An uncertainty in the correction value of 0.5% is estimated.

The final calculated beam energy at the ionization chamber was 160.3 ± 0.6 MeV.

The range spread may be obtained by differentiating the range energy curve. The expected fluctuation in the path length of the protons is Gaussian with the ratio of the rms fluctuation, σ, to the total path length P given by

$$\frac{\sigma}{P} = \left[\sqrt{\frac{102.2}{Mc^2}} \; f \left(\frac{E}{Mc^2} \right) \right], \tag{6}$$

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11. U. Fano, *Ann. Rev. Nucl. Sci.* 13, 1 (1963)

12. R. W. Peelle, unpublished. These data use essentially the same parameters used by Bichsel.

13. R. M. Sternheimer, *Phys. Rev.* 115(1), 137 (1959).

14. M. Rich and R. Madey, *Range-Energy Tables*, UCRL-2301 (March 1954).

15. C. Williamson and J. P. Boujot, *Tables of Range and Rate of Energy Loss of Charged Particles of Energy 0.5 to 150 MeV*, Report No. 2189, Centre d'Etudes Nucléaires de Saclay.

16. H. A. Bichsel, *Higher Shell Corrections in Stopping Power*, Tech. Rept. No. 3, Department of Physics, University of Southern California, Los Angeles.

TABLE 2. Comparison of Published Values for the Path Length of Protons in Copper and the Value for dE/dx

E (MeV)	Bischel		Peelle			Sternheimer			Rich and Madey			Williamson and Boujot		
	R (g/cm^2)	dE/dx (MeV g^{-1}cm^{-2})	R (g/cm^2)	dE/dx (MeV g^{-1}cm^{-2})	%ΔR	R (g/cm^2)	dE/dx (MeV g^{-1}cm^{-2})	%ΔR	R (g/cm^2)	dE/dx (MeV g^{-1}cm^{-2})	%ΔR	R (g/cm^2)	dE/dx (MeV g^{-1}cm^{-2})	%ΔR
140	21.171	3.847	21.124	3.856	+0.23	21.63	3.767	-2.1	~	~		21.648	3.753	-2.2
150	23.83	3.673	23.779	3.682	+0.25	24.34	~	-2.1	23.85	3.661	+0.31	24.412	3.59	-2.2
160	26.614	3.519	26.555	3.528	+0.27	27.19	3.445	-2.1	~	~				
170	29.513	3.383	29.447	3.391	+0.24	~	~	~	~	~				
180	32.524	3.261	32.452	3.268	+0.21	33.23	2.192	-2.2	~	~				

where Mc^2 is the rest mass energy of the proton in MeV, E is the kinetic energy of the proton, and f (E/Mc^2) is obtained from Bichsel's[10] work for range straggling.

For 160-MeV protons, f (E/Mc^2) = 3.6% and σ = 0.32 g/cm^2 when P is 27 g/cm^2 as above. The measured straggling standard deviation obtained from the differential range-energy curve is 0.34 $\pm$ 0.05 g/cm^2.

Measurement of the Proton Energy by Flight Time

The proton energy was also determined by measuring the flight time of the protons, with the apparatus shown in Fig. 11, over a distance of 355 $\pm$ 1 cm. With the "A" and "B" detectors positioned about 75 cm apart, a calibration curve of stop delay vs analyzer channel number was obtained. The "B" detector was then moved 355 cm farther away, and the experiment was repeated. The time required for the protons to travel 355 cm was obtained from the amount of change in the stop delay required to re-establish time coincidence. From these data, which are shown in Fig. 12, the time required for the protons to travel 355 cm was 23.26 $\pm$ 0.1 nsec. The uncertainty, thought to come from the differential nonlinearity of the time-to-pulse-height converter, arises from consideration of several points along the curve in Fig. 12.

The error in the measurement of the flight path is 0.27%. A 1% standard error in the delay line calibration also exists, so that the total error in the measurement of the flight time is 1.1%. The proton velocity is then 15.26 $\pm$ 0.17 cm/nsec. Correcting for the energy loss (1.38 MeV) of the protons in the "A" detector and air, the beam energy determined by flight time is 153.38 $\pm$ 4.1 MeV.

Conclusions to the Proton Beam Measurements

The energy obtained from the range-energy measurement, 160.3 $\pm$ 0.6 MeV, and that obtained from the time-of-flight measurement, 153.38 $\pm$ 4.1 MeV, are in mild disagreement. Both values, however, are in agreement with published[17] values for the beam energy of 158 $\pm$ 2 MeV.

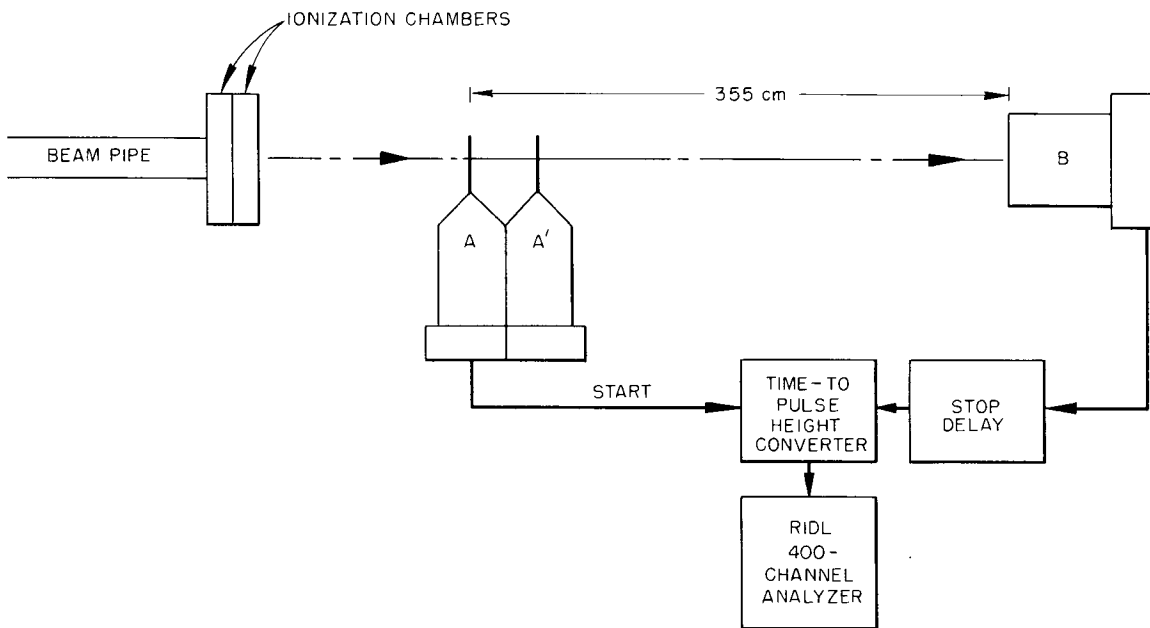17. F. T. Howard, Cyclotrons and High Energy Machines, ORNL-2644 (1958).

Fig. 11.   Block Diagram of Components for Proton Time-of-Flight Measurements.
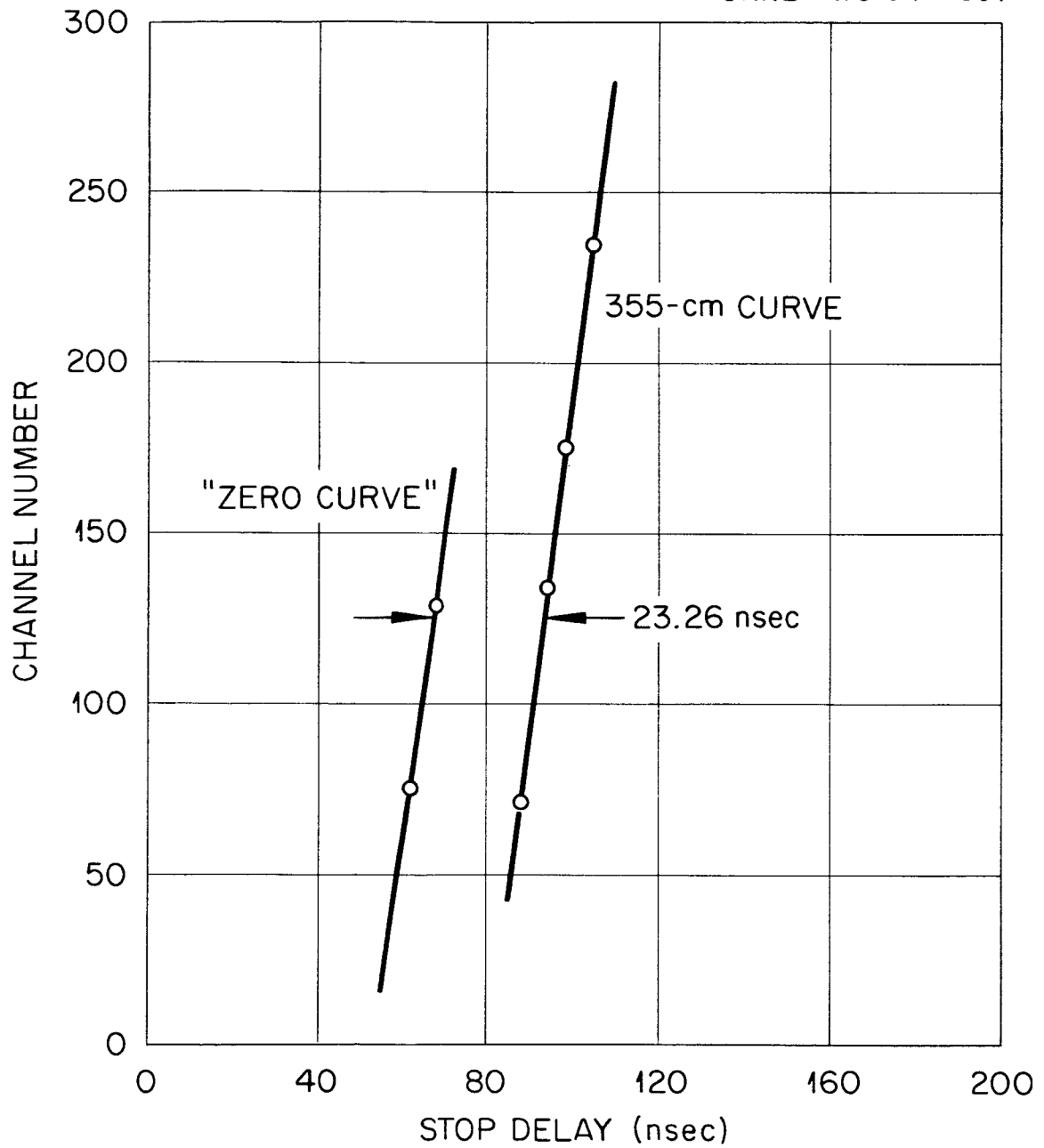
Fig. 12. Flight-Time Curves for Measuring Proton Beam Energy.

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